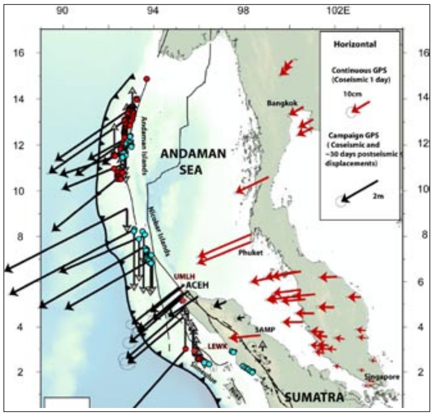

Earthquake and Tsunami Source

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Introduction

During the 26 December 2004 Great Sumatra-Andaman earthquake, heterogeneous slip amounts and velocities occurred across a vast area of the plate interface. Large and rapid slip produced the initial subevent, itself a potent seismic and tsunami source comprising the first one-third of the total rupture length. The initial subevent precipitated further northward progression of slip, dynamically extending the full rupture length threefold alongstrike to ~1600 km. Rapid early slip was resolved best teleseismically for the first several hundred seconds, whereas slower slip proved sufficiently large to be geodetically recorded locally, regionally, and worldwide. Also, deformation recorded geologically by the uplift and subsidence of coral reefs constrained the alongstrike and downdip pattern of fault slip. The extremely long duration and spatial extent of the source presented challenges for observation, analysis, and interpretation of the earthquake source. Robust imaging using all available data, however, can now explain many aspects of the complicated and protracted source evolution.

The 26 December 2004 Great Sumatra-Andaman Earthquake

The lengthy and uneven rupture process began at 3.0° N off the northwestern end of Simeulue Island on the plate interface megathrust fault (Figure 1). The early onset of rupture led to rapid large slip unilaterally toward the north, producing a large slip patch of up to 18 m of slip across the downdip width for several hundred kilometers alongstrike, an area of roughly 10,000 km^2

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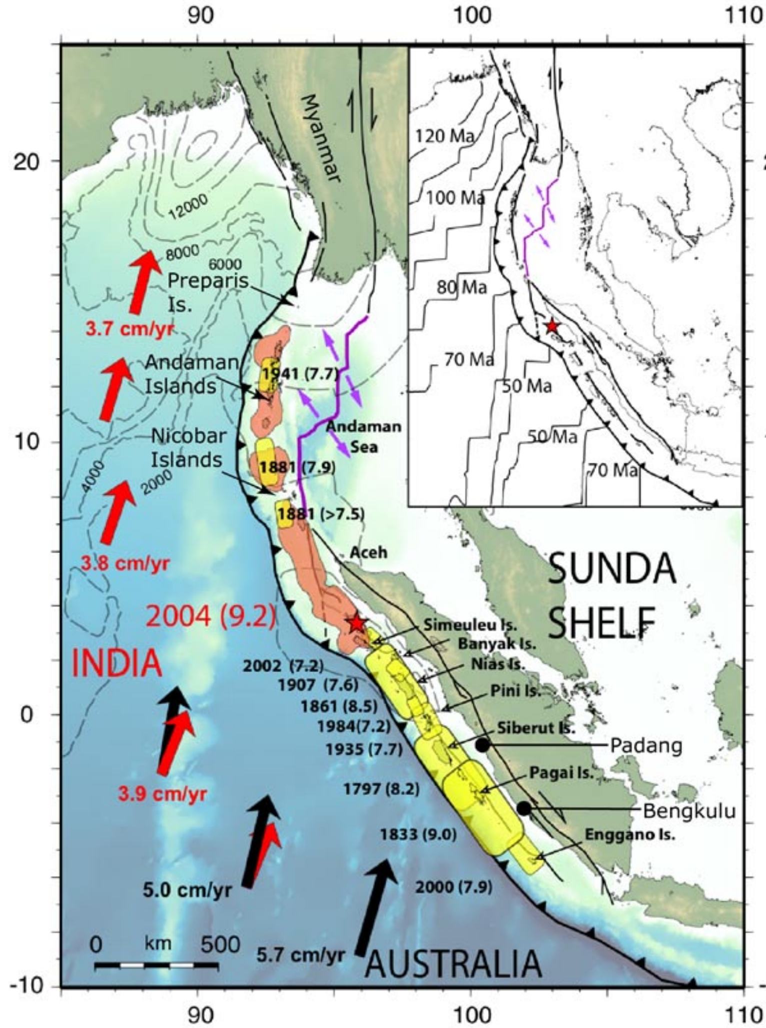

Figure 1. *The Sunda megathrust plate boundary, along which the 2004 Sumatra-Andaman and 2005 Nias-Simeulue earthquakes occurred. Plate motion vectors relative to Sunda (black arrows for Australia, gray for India) and plate ages and major boundaries are shown (inset). Rupture zones of historic and prehistoric earthquakes are shown in light gray, and areas of >5 m slip in the 2004 earthquake are shown in darker gray. Sediment thickness contours at 2,000-m intervals are shown as dashed lines (from Subarya et al. 2006).*

(Chlieh et al. 2006). Rupture then continued northward rapidly to 10° N, then evidently slowed and finally stopped at about 15° N (Meltzner et al. 2006). Along the way, several additional large slip patches occurred, but none were as large as the initial one (e.g., Banerjee et al. 2006). The character of rupture is thought to have changed upon passing into the tectonic regime north of 10° N (bordered by back-arc spreading to the east); after this, it slowed down until it clearly was no longer producing a tsunami from 11° N to 15° N (e.g., Geist et al. 2006).

Generally, the southern third of the rupture had been regarded as potentially seismogenic. From this portion, the earthquake rupture began and the tsunami that destroyed the western shore of Sumatra's Aceh province originated. The fact that rupture then cascaded northward well beyond

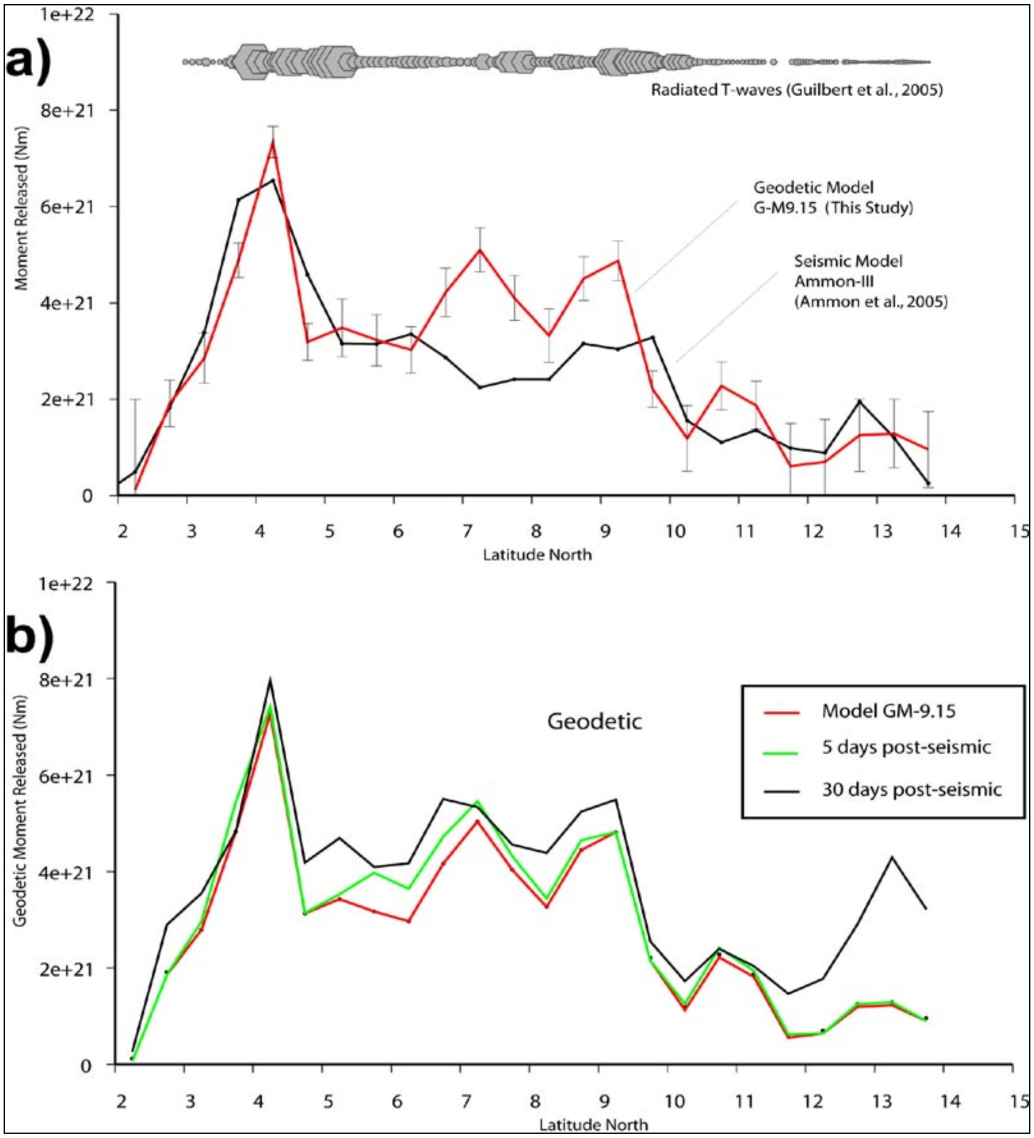

Figure 2. *(a) Coseismic moment release alongstrike, estimated by seismological and geodetic methods and showing T-wave energy radiation across the top. (b) Comparison of coseismic and postseismic moment release alongstrike, showing 5-day and 30-day progression of afterslip (from Chlieh et al. 2006). While it had been generally agreed that the tsunamigenic portion of the rupture extended only to ~9° N (Lay et al. 2005), recent tide gauge data indicate that tsunamigenic rupture continued to 11° N (Neetu et al. 2005) and that significant total slip extended past 14° N and perhaps even to 15° N (Meltzner et al. 2006).*

this area was quite surprising, as rupture sped energetically for ~600 km more along a section of the Sunda arc that had not been considered either seismogenic or tsunamigenic. Through this midsection of the rupture, wherein slip was still large and fast, more devastating tsunami energy was unleashed (Figure 2). Evidently, the northernmost 400 km was not especially tsunamigenic because the fault was slipping less energetically by then, but the slower—yet still substantial—slip here is least well understood (Bilham 2005). Rupture beyond 10° N continued to radiate high-frequency energy (Ni et al. 2005; Guilbert et al. 2005), yet the amount of coseismic slip and afterslip decreased considerably beyond this, diminishing to zero to the north (Figure 2).

Accompanying papers in the special issue of *Earthquake Spectra* (see accompanying DVD) review source observations from seismology (Kanamori 2006, special issue) as well as geology and geodesy (Hudnut 2006, special issue) in greater detail than the present summary paper does. Aspects of the rupture process and tsunamigenesis remain enigmatic, not only because of limited data but also because of challenges to theory and modeling, and will certainly be the subject of much continuing study in coming years. In addition to reviewing the Sumatra-Andaman earthquake source properties, this paper—and especially its extended companion version (Hudnut 2006, special issue)—also reviews what had been known of the seismic and tsunami hazards along this part of the Sunda arc, the possible influence of tectonic features on the rupture process, and new concerns about future earthquakes and tsunamis off Sumatra.

Stress caused by the great 26 December 2004 Sumatra-Andaman event evidently led to the large 28 March 2005 Nias-Simeulue event (M = 8.6) directly to the south (McCloskey et al. 2005; Briggs et al. 2006), leading to concerns of a domino effect toward the southeast (Nalbant et al. 2005). Between 1° S and 5° S, the megathrust had last ruptured in a major event pair that occurred in 1797 and 1833 as determined from historical accounts (McCann et al. 1979; Newcomb and McCann 1987) and also growth rings dated in corals that were disturbed by uplift and submergence during the earthquakes (Zachariasen et al. 1999; Natawidjaja et al. 2004, 2006). This unruptured segment therefore remains a source of heightened concern, creating great uncertainty for the highly populated yet low-lying western Sumatra coastal cities of Padang and Bengkulu (Sieh 2005), which are shown on Figure 1.

What Was Known and Anticipated—or Not?

The historic and prehistoric sequence of great events along the subduction zone from the study of historical records and fossil evidence from corals showed high risk of an M ~ 9 tsunamigenic earthquake from just south of the Batu Islands (of which Pini Island, shown in Figure 1, is one) to the southeast, similar to an event pair that had struck in 1797 and 1833 (Newcomb and McCann 1987; Zachariasen et al. 1999; Natawidjaja et al. 2006). An earthquake of M ~ 9 was considered highly likely in even the most recent probabilistic seismic forecasts (e.g., Petersen et al. 2004), and it was also generally held that such a great event would probably be tsunamigenic.

Missing, however, was an appreciation for the earthquake and tsunami hazard from north of the island of Sumatra. As explained more fully in Hudnut (2006, special issue), McCann et al. (1979) had stated what became the accepted idea: there did "not appear to be great earthquakes associated with the Sunda arc in the Andaman-Nicobar region." Because plate convergence becomes highly oblique northward from 3° N (e.g., McCaffrey et al. 2000), and because strike-slip motion is being accommodated on the Great Sumatran and Andaman faults, it was generally believed that the efficiency of relative movement across the plate interface was being resolved into fault-normal and fault-perpendicular components—which is called *slip partitioning*—in such a way that the trench-normal convergent component was slight or negligible (Prawirodirdjo et al. 1997; Genrich et al. 2000; McCaffrey et al. 2000).

A significant change in tectonic setting, however, occurs at about 10° N, midway up the Andaman and Nicobar (A&N) island chain between Car Nicobar Island and Little Andaman island. Here, the ridge-transform system beneath the Andaman Sea (Figure 2) abuts and interacts within the back-arc of the subduction zone (Curray 2005). Along the arc, variations in the sediment thickness and age of the subducting plate may also help to determine the change in coupling across the plate interface (e.g., Chlieh et al. 2006). Recent results reviewed by Hudnut (2006, special issue) indicate that oblique convergence of 14 ± 4 mm/year occurs, so the former assumption that trench-normal convergence was negligible through the Andaman Islands was gradually being disproved by using GPS at about the time the event happened (e.g., Bilham 2005).

Little is known even now about the northern extent of the seismic and tsunami hazard, although early historical records are being searched for evidence of events off Myanmar. Evidently, slip in the 2004 Sumatra-Andaman event extended as far north as Preparis Island at 14.9° N (Meltzner et al. 2006). Although it is conceivable that seismic and tsunami hazards could have been more clearly recognized and characterized for the convergence across the plate boundary from 10° N to the northern extreme end, the interseismic deformation in this area remains unclear even with the benefit of hindsight.

Hence, before this event, no one had ever argued for the possibility of an M ~ 9 rupture extending northward through the A&N Islands. The northernmost 800 km of the 2004 earthquake rupture was unanticipated, and the southern half of this part of the rupture was tsunamigenic and caused widespread damage in Thailand, Myanmar, Sri Lanka, and India. These areas would not have been considered to be in significant danger in any tsunami hazard models prior to this event. That is, because there was not thought to be as great a seismic threat from the subduction zone north of 6° N and up to 11° N, there was thought to be a relatively low tsunami threat to these coastlines, which ended up being very heavily damaged in 2004.

What Might Have Been Known, and How Can We Do Better?

Hypothetically, this underestimation of the earthquake and tsunami hazard did not have to happen. Had there been an array of continuous GPS stations operating for several years, better constraints on the seismic hazards would certainly have been possible. Furthermore, had investigators been able to sample corals in this region, as had been done off Sumatra to the south, the paleoearthquake history would certainly also have helped in quantifying hazards for this section of the subduction zone. Systematic searches for paleotsunami deposits would have helped to quantify earthquake and tsunami hazards. As an added benefit, these studies and monitoring arrays will then also provide valuable data after future great earthquakes.

After future great earthquakes, better earthquake magnitude and slip distribution estimates will be made much more rapidly (e.g., Ni et al. 2005; Stein and Okal 2005; Menke and Levin 2005; Blewitt et al. 2006). From both seismologic and geodetic global networks, data telemetered in real time will be available to tsunami warning centers, where improved algorithms will allow more refined analysis (Weinstein et al. 2005). For basinwide tsunamis in the Indian or Pacific Ocean, such systems should help greatly. Also of great concern, however, are situations such as that faced by the western Sumatra coast off Padang and Bengkulu, where the tsunami warning time for a M ~ 9 earthquake may be only 20 minutes. Even the most technically advanced system will be unable to prevent a potential disaster there, although efforts in that coastal area are being made to provide not only a warning system but also improved tsunami hazard assessment, education, and evacuation planning.

As shown by Synolakis (2006, special issue), while much remains to be learned about tsunami propagation, models can now be used to better anticipate the impact of future events. Also, Dengler in this volume explains the importance of education for ensuring effective use of the best available scientific information. As described by Weinstein et al. (2005), an effective global tsunami warning system is needed that combines three components for tsunami hazard mitigation: (1) tsunami hazard and risk assessment, (2) warning guidance, and (3) preparedness. Furthermore, Synolakis et al. (2006) give a more detailed assessment of what can be done to improve tsunami mitigation worldwide for the future.

Discussion

As the Sumatra-Andaman and Nias-Simeulue events have shown, earthquakes are extremely unpredictable. For example, because of the very oblique subduction from 5° N to the north, seismic and tsunami hazards had been considered negligible along the part of the megathrust from ~5° N to ~11° N that contributed heavily to the source of one of history's deadliest natural calamities. On the other hand, one can argue that the earthquake and tsunami hazard associated with the megathrust south of ~5° N was relatively well appreciated. Also importantly, one of the major uncertainties in seismic hazard models involves rupture segmentation, and the data from the 2004 Sumatra-Andaman and 2005 Nias-Simeulue earthquakes have certainly proved illuminating in this regard, as discussed in Hudnut (2006, special issue). While some researchers discover new hope and optimism among these new findings, others point out that we are clearly still far from a comprehensive understanding. Are these natural phenomena inherently chaotic? Are the glimmers of predictability that we observe within the system, such as the similarity between the 2005 event and the 1861 event, or the evidently stationary nature of the Simeulue segment boundary, merely coincidental? For example, even if we were to obtain a perfect understanding of fault segmentation on Simeulue Island, we also must learn how ruptures may cascade from one segment to another.

Any pause in a rupture cascade may be rapid in terms of geological time, but to humans a pause of days to decades seems lengthy. At least, such pauses give us a chance to model and try to anticipate what may come next (e.g., McCloskey et al. 2005; Sieh 2005; Pollitz et al. 2006). A natural distinction in the time scale occurs, of course, for dynamic and static cases. Once the propagating waves have dissipated from the system, the static stress changes and any transient physical processes remain in effect and can continue forcing the cascading phenomenon. We ask such questions as "What is coseismic versus postseismic rupture?" or "Is this a cascading complex source with many subevents, or is it several discrete events?" The answers lie in recognizing the continuum in natural rupture phenomena.

While all of this inquiry may help in understanding earthquake source physics, it also means that sources are even more varied and complicated than we had realized before the advent of modern broadband seismic and continuous GPS data. That is, state-of-the-art global and regional data for these megathrust events have shown us details of the source that we could not have obtained for, say, either the 1960 Chile or 1964 Alaska event. Now we are able to pursue more pointed questions about source physics, taking advantage of all the new data. Our ability to model the source and propagation, as well as the resultant deformation field, has certainly improved greatly in the last several decades. It is nevertheless clear that we would have benefited greatly from having more of certain types of data for these earthquakes. For example, for the Sumatra-Andaman event, continuous GPS data from the A&N Islands, as well as more water level data from the Indian Ocean, would allow us to better model the second half or northern portion of the earthquake source and how it related to the formation of the tsunami. We would do well to collectively instrument source areas of potential future megathrust events so as to capture, in even better detail, their source properties the next time we have such an opportunity to learn from nature. At the same time, such arrays can help to provide accurate and timely warning guidance to disaster response officials.

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Figure 3. *The trim line at a small headland at Lhoknga. This hill was previously covered by dense jungle to the waterline (photo: J. Borrero)*

Figure 4. *Two views of the same location illustrating the enormous uplift that occurred during the March 2005 earthquake. The top photo shows the location at Lahewa Harbor on Nias Island, Indonesia, after the December earthquake and tsunami. The man is pointing to the water line from that tsunami. The second photo was taken at exactly the same location after the March earthquake, illustrating the uplift of the entire harbor (a pier and wharf are visible in the background). The uplift was approximately 2.5 meters. The total tide range is under 1 meter, so this uplift has had a major impact on the harbor and way of life here (photos: J. Galetzka)*